Precision Measurements of Kinematic Scan for Fluctuations of (Net-)proton Multiplicity Distributions in Au+Au Collisions from RHIC-STAR

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STAR Collaboration

Outline

1. *Motivation*

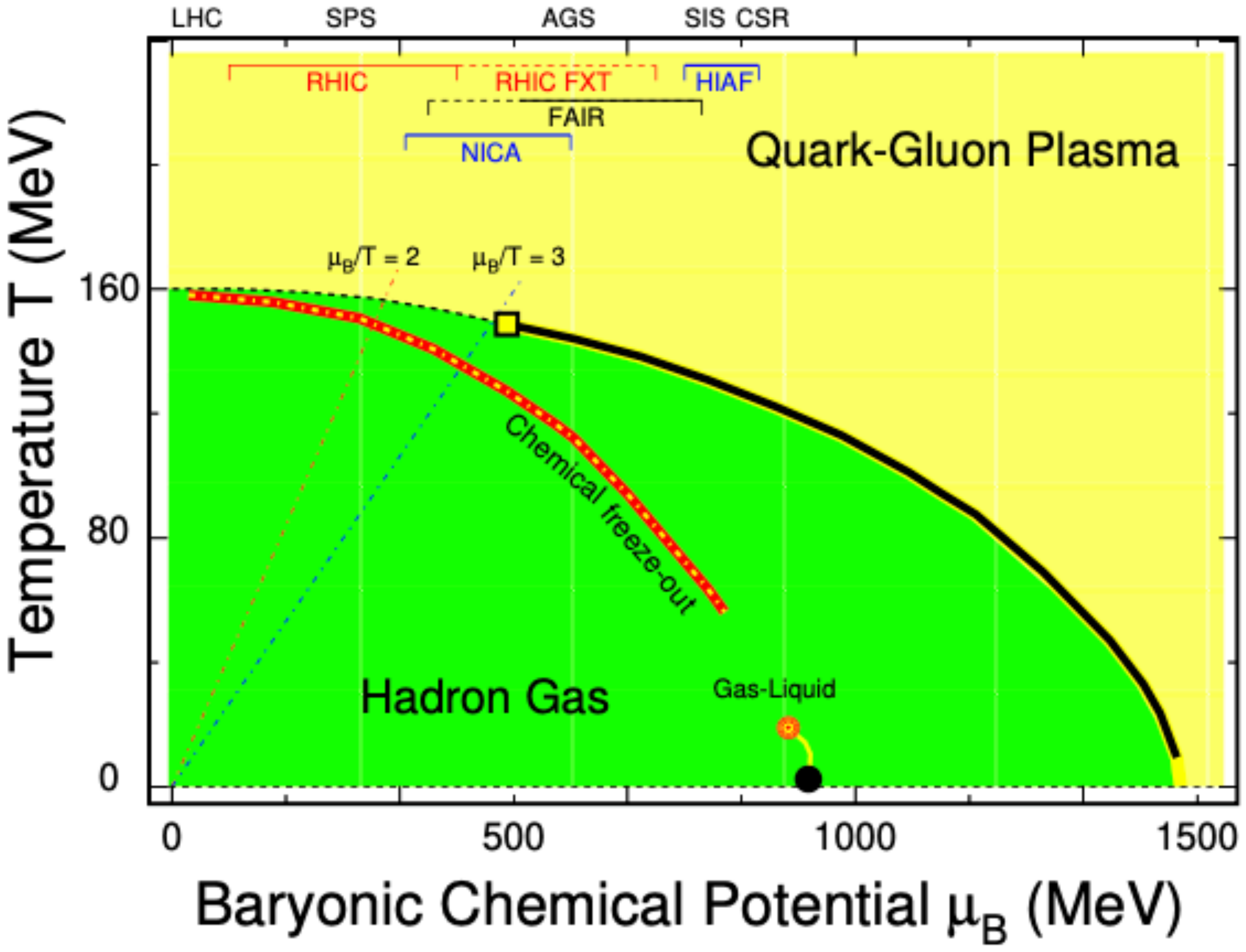
2. *STAR Experiment*

3. *Selected Results*

    1) *Net-proton Number Distributions*
    2) *Rapidity / p_{T} Scan of (Net-)Proton (Factorial) Cumulants*
    3) *Energy Dependence and Significance*
    4) *Finite-Size Scaling Study with C_2 and C_4*

4. *Summary*

Motivation



[1]

- Lattice QCD: A smooth crossover at small μ_B
- Model predictions: First-order phase transition at high μ_B and a critical end point

❖ Needs confirmation by experimental data!

- Beam energy scan program in STAR maps the proton high moments as a function of μ_B and T by varying the collision energy

[1]X.Luo, et al.: Particles 3(2020)2,278-307

Motivation

N: Event-by-event multiplicity

$\delta N = N - \langle N \rangle$

Cumulants

- ❑ $C_1 = \langle N \rangle$
- ❑ $C_2 = \langle \delta N^2 \rangle$
- ❑ $C_3 = \langle \delta N^3 \rangle$
- ❑ $C_4 = \langle \delta N^4 \rangle - 3\langle \delta N^2 \rangle^2$

1) Related to the correlation length ξ[1]

$C_2 \sim \xi^2$ and $C_4 \sim \xi^7$

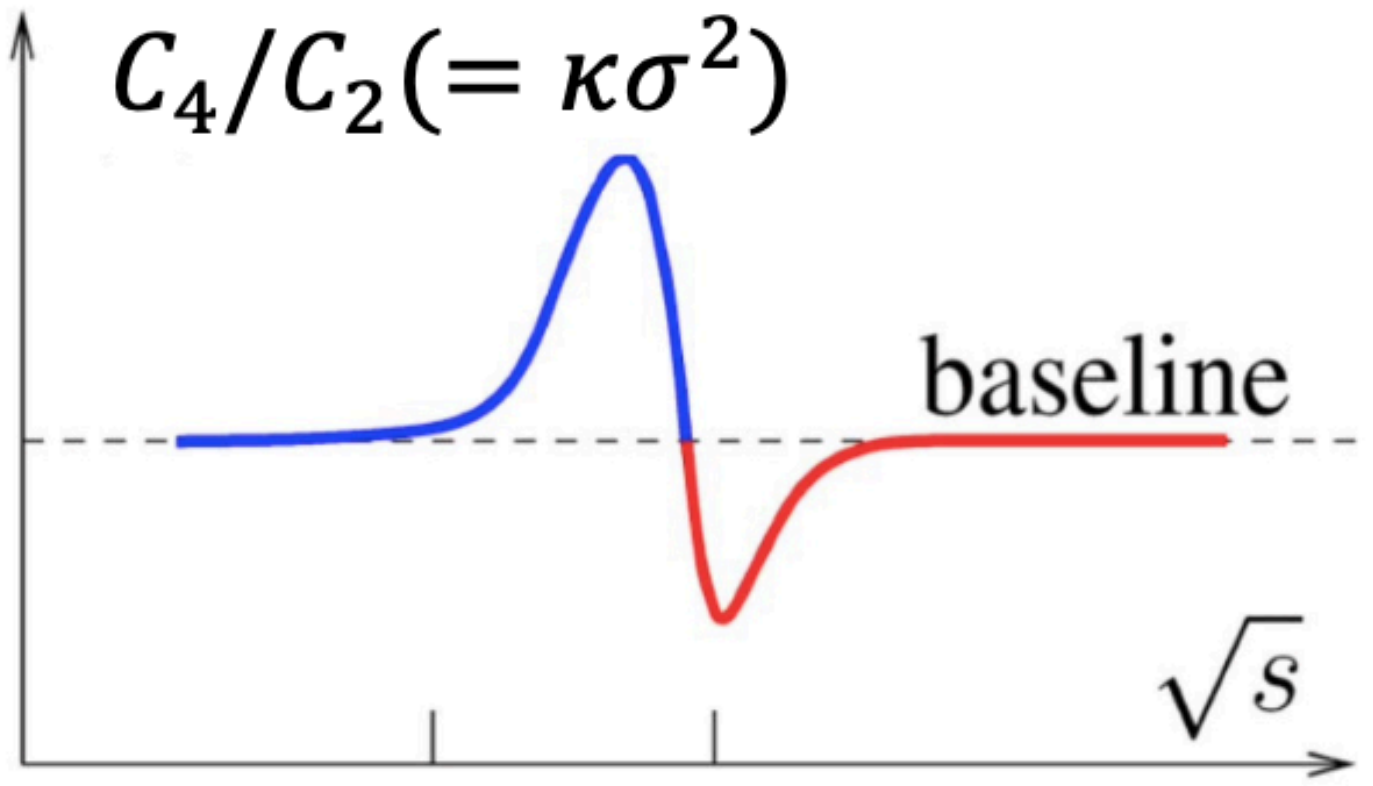
ξ diverges at the critical point

Higher order → More sensitive!

2) Related to the susceptibility χ^q

$$\frac{C_4^q}{C_2^q} = \frac{\chi_4^q}{\chi_2^q}$$

Directly comparable to the model[2-5] calculations!



Non-monotonic energy dependence of C_4/C_2 for the conserved baryon number (using protons as a proxy) indicates the existence of a critical region.[1]

Factorial Cumulants

- ❑ $\kappa_1 = C_1$
- ❑ $\kappa_2 = -C_1 + C_2$
- ❑ $\kappa_3 = 2C_1 - 3C_2 + C_3$
- ❑ $\kappa_4 = -6C_1 + 11C_2 - 6C_3 + C_4$

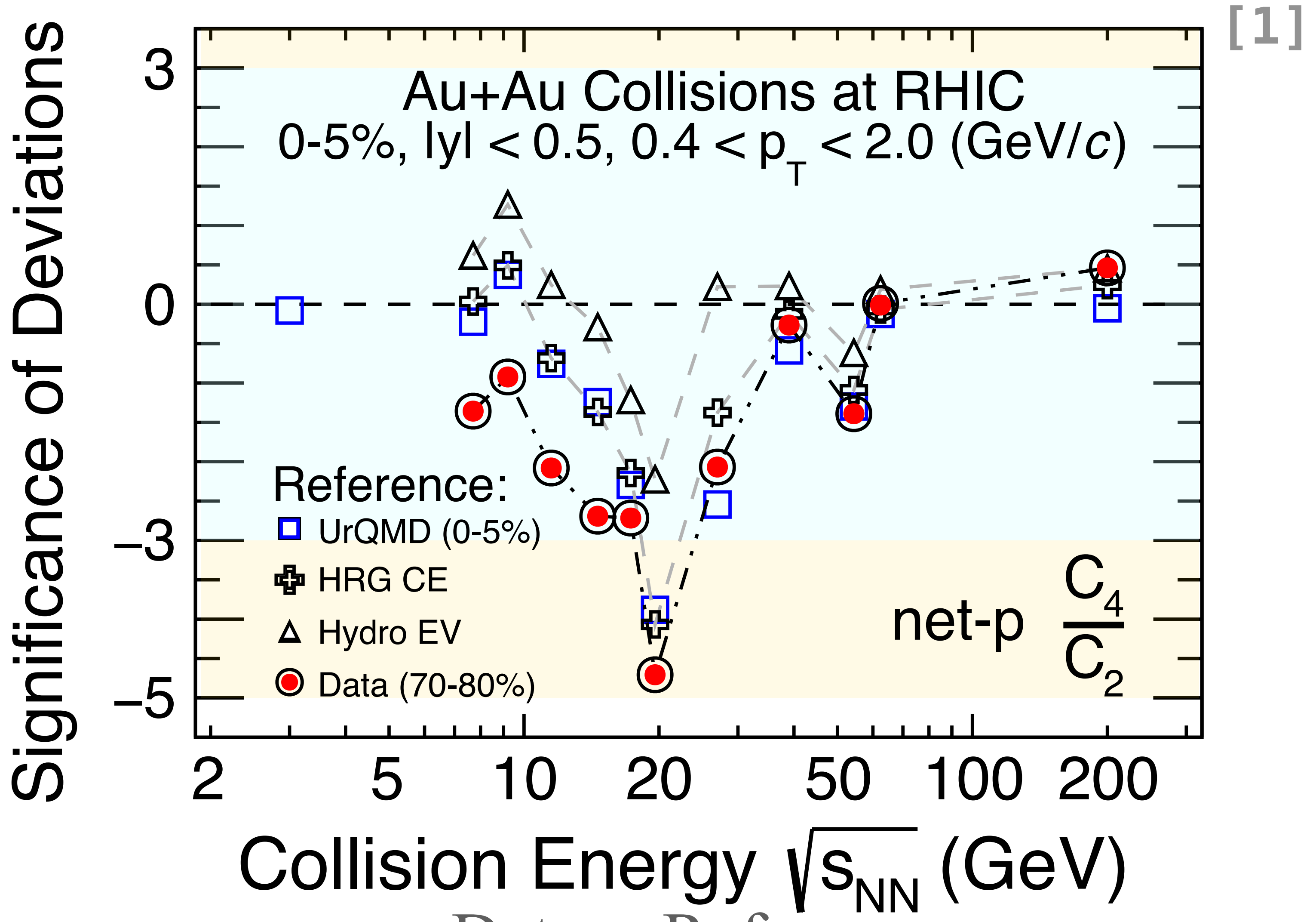
1) Can be expressed by linear combinations of ordinary cumulant;

2) Directly capture and are sensitive to genuine multi-particle correlations.

- Higher-order cumulants of conserved charges serve as an important probe in the search for QCD critical end point

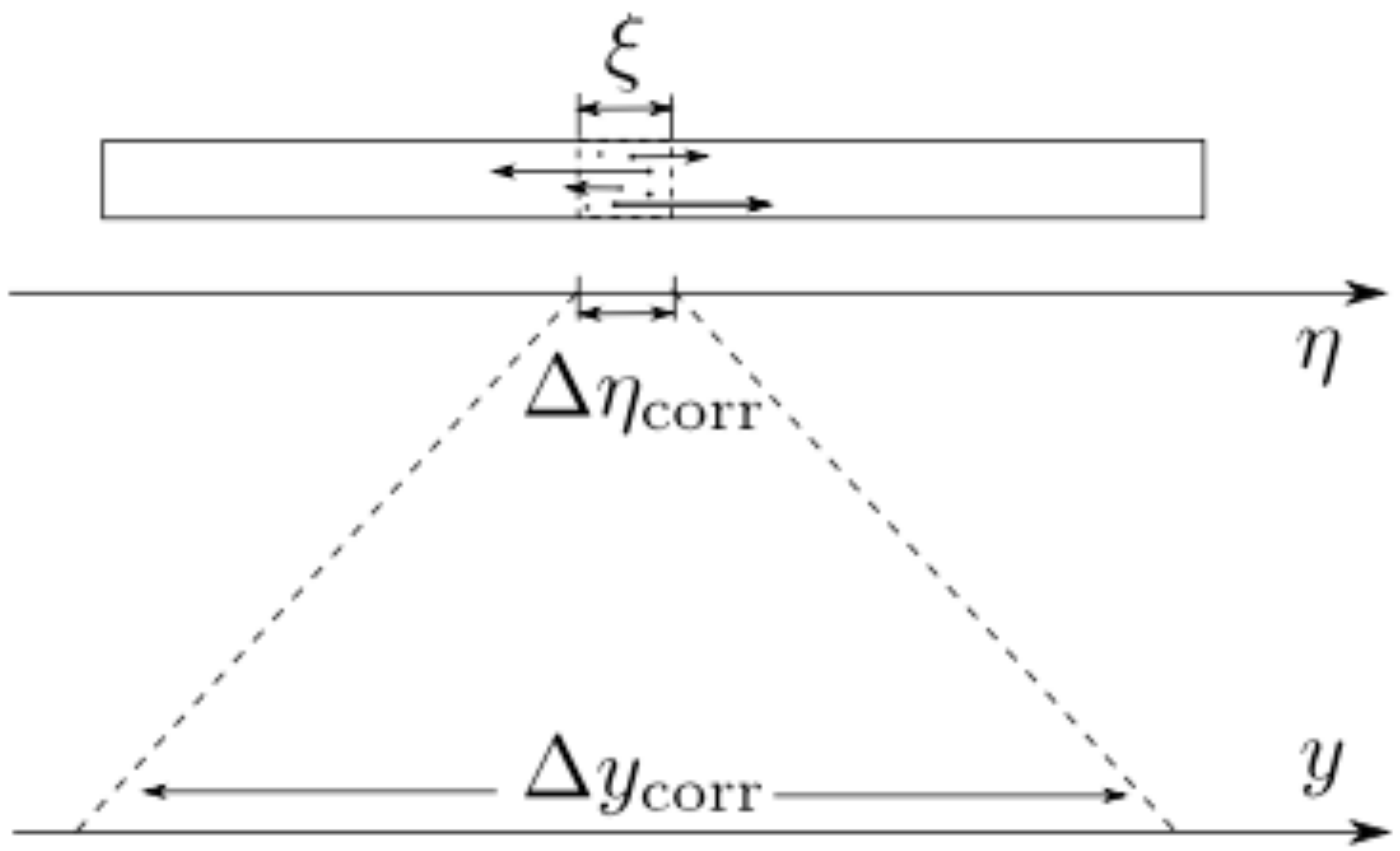
[1]M.A.Stephanov: Phys.Rev.Lett. 107(2011),052301
[2]R.V.Ravai and S. Gupta: Phys.Lett.B 696(2011),459-463
[3]S.Ejiri, F.Karsch, K.Redlich: Phys.Lett.B 633(2006),275-282
[4]A.Bazavov, et al.: Phys.Rev.Lett. 109(2012),192302
[5]A.Borsanyi, et al.: Phys.Rev.Lett. 111(2013),062005

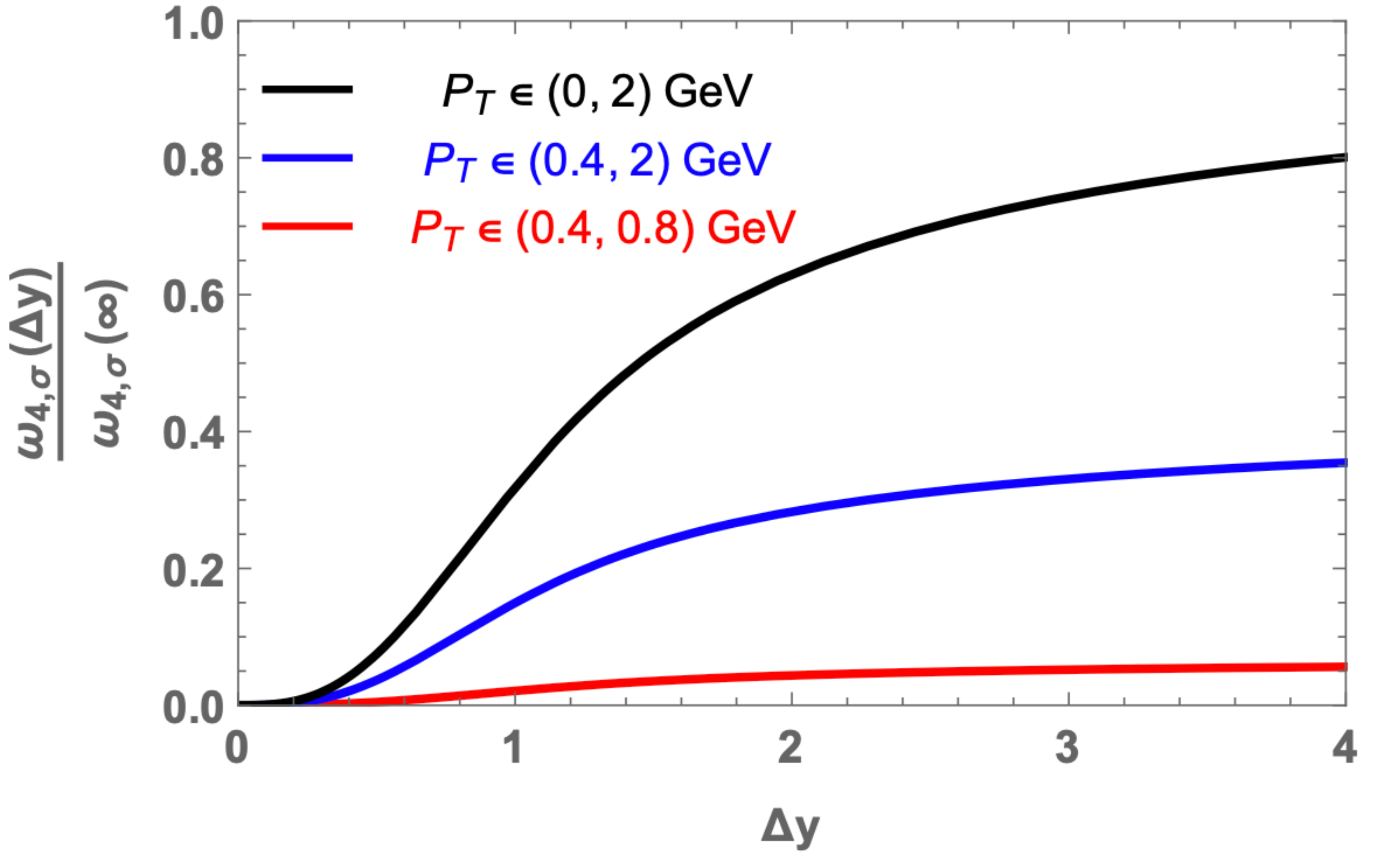
Motivation



$$\text{Significance} = \frac{\text{Data} - \text{Ref.}}{\sigma_{\text{total}}}$$

Data: net-proton C_4/C_2 in 0-5% collisions





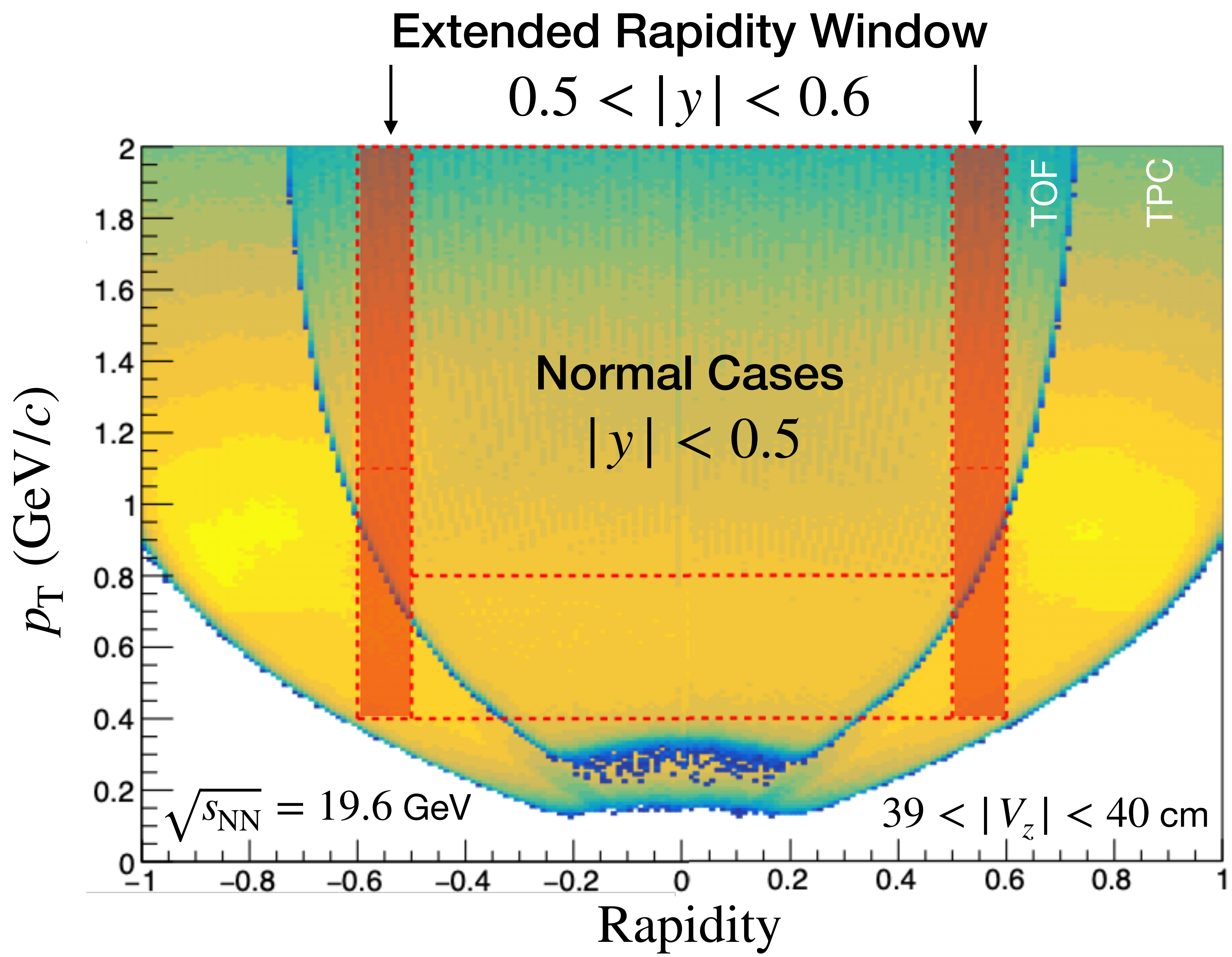
1. Long-range phenomena near critical point: increasing the measurement window in y and p_T magnifies the contribution to normalized cumulants;
2. For small rapidity window $\Delta y \ll \Delta y_{corr}$, and near the critical point, we expect $\kappa_n \sim (\Delta y)^n$[2];
3. The wide and uniform acceptance of the detector provides us with the opportunity to conduct kinematic scan.

[1]STAR: arXiv:2504.00817[nucl-ex]
[2]B.Ling and M.A.Stephanov: Phys.Rev.C 93(2016)3,034915


EEMC
Magnet
MTD
BEMC
eTOF
TOF
TPC
iTPC
EPD
STAR Detector System

Data Sets

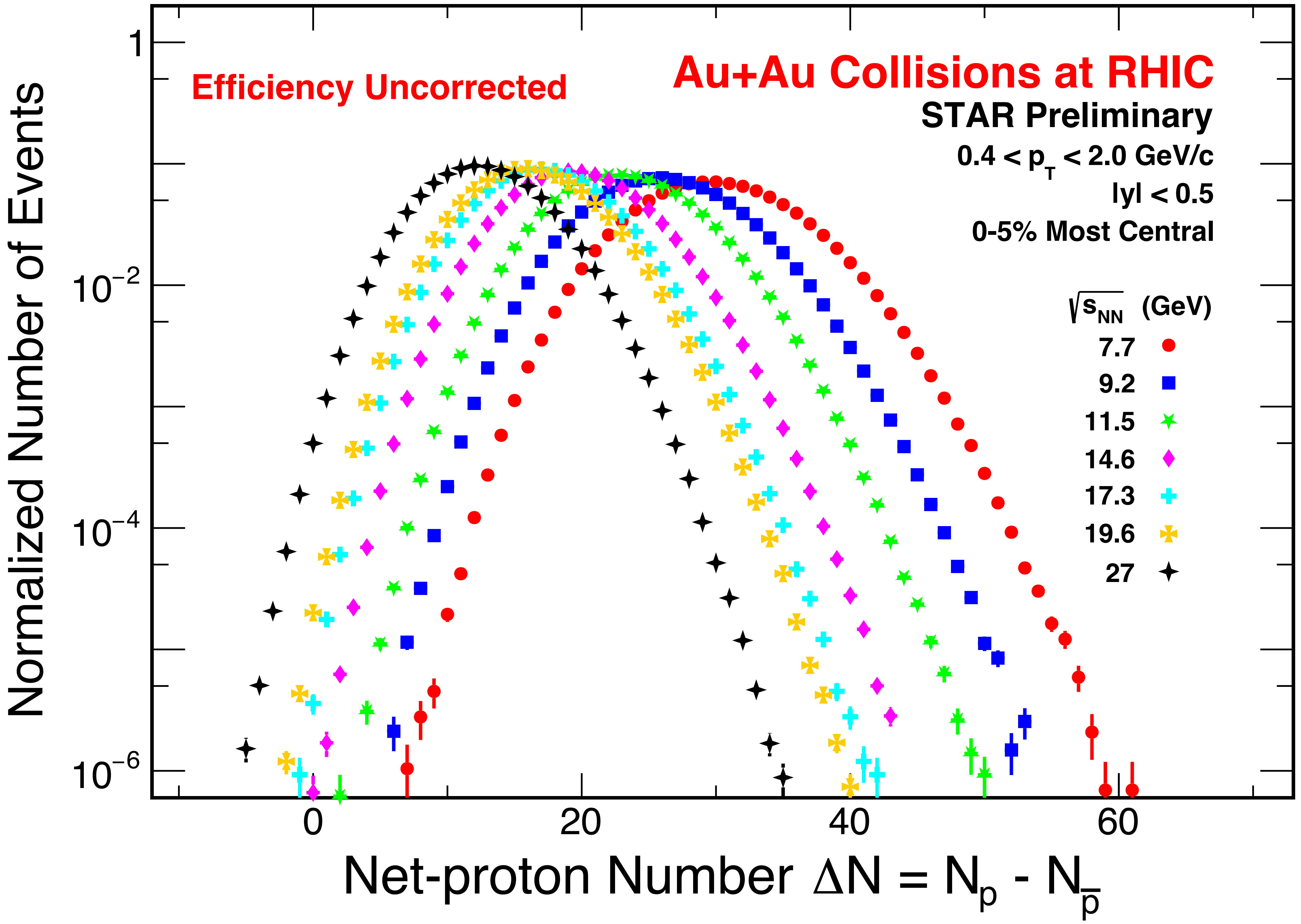
Energy (GeV)		7.7	9.2	11.5	14.6	17.3	19.6	27
|Vz| Cut (< cm)	|y| < 0.5	50	50	50	50	50	50	27
	|y| < 0.6	20	30	30	40	40	40	-
Number of Events (M)	|y| < 0.5	45	78	116	178	116	271	220
	|y| < 0.6	17	42	61	133	94	220	-
	|y| < 0.5 (BES-I)	3	-	6.6	20	-	15	30

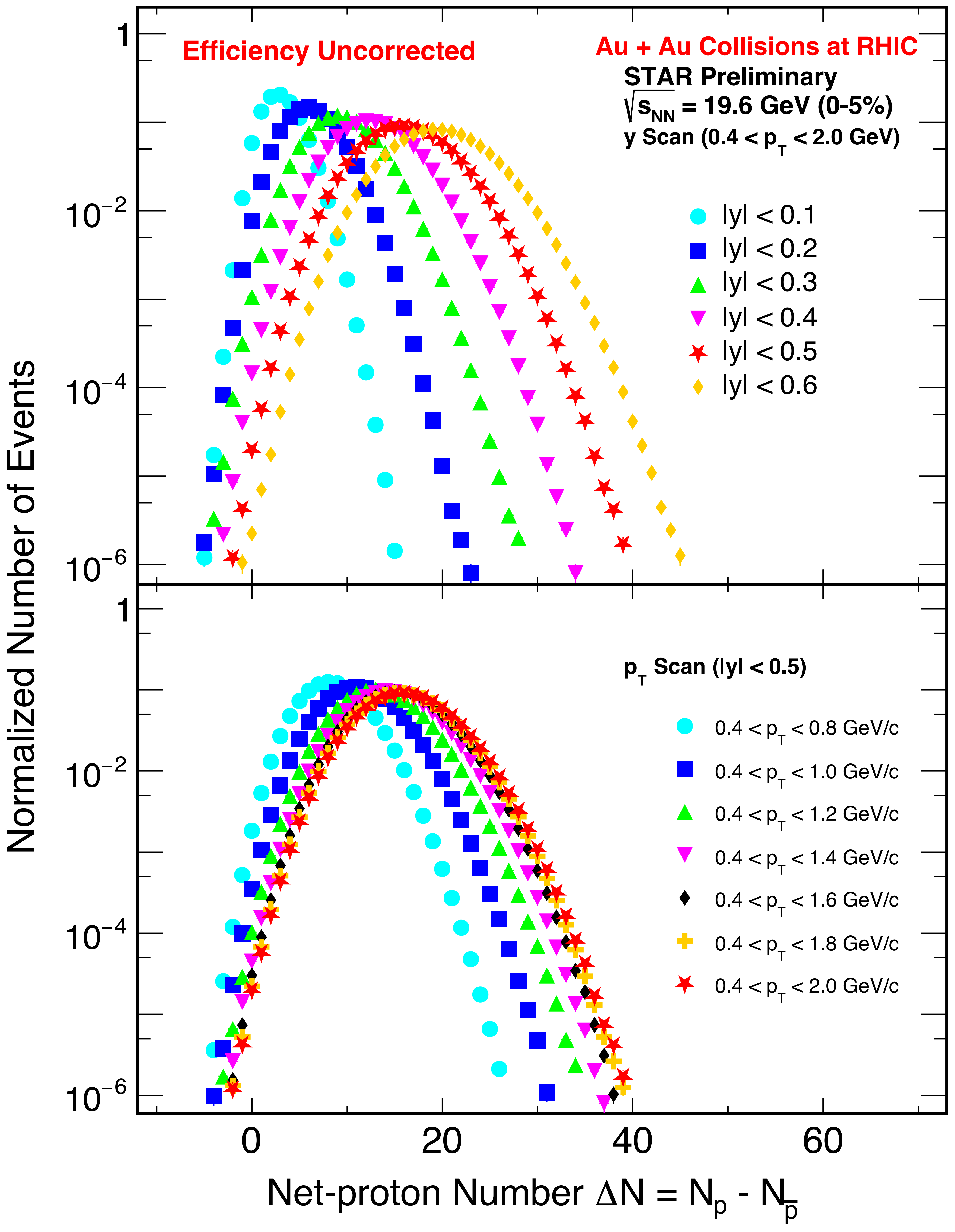


1. With appropriate cut selection and PID method, we ensure the proton purity larger than 95%;

2. The selection of vertex-Z (V_z) is constrained by the requirements for purity and detector acceptance.

Net-proton Number Distributions

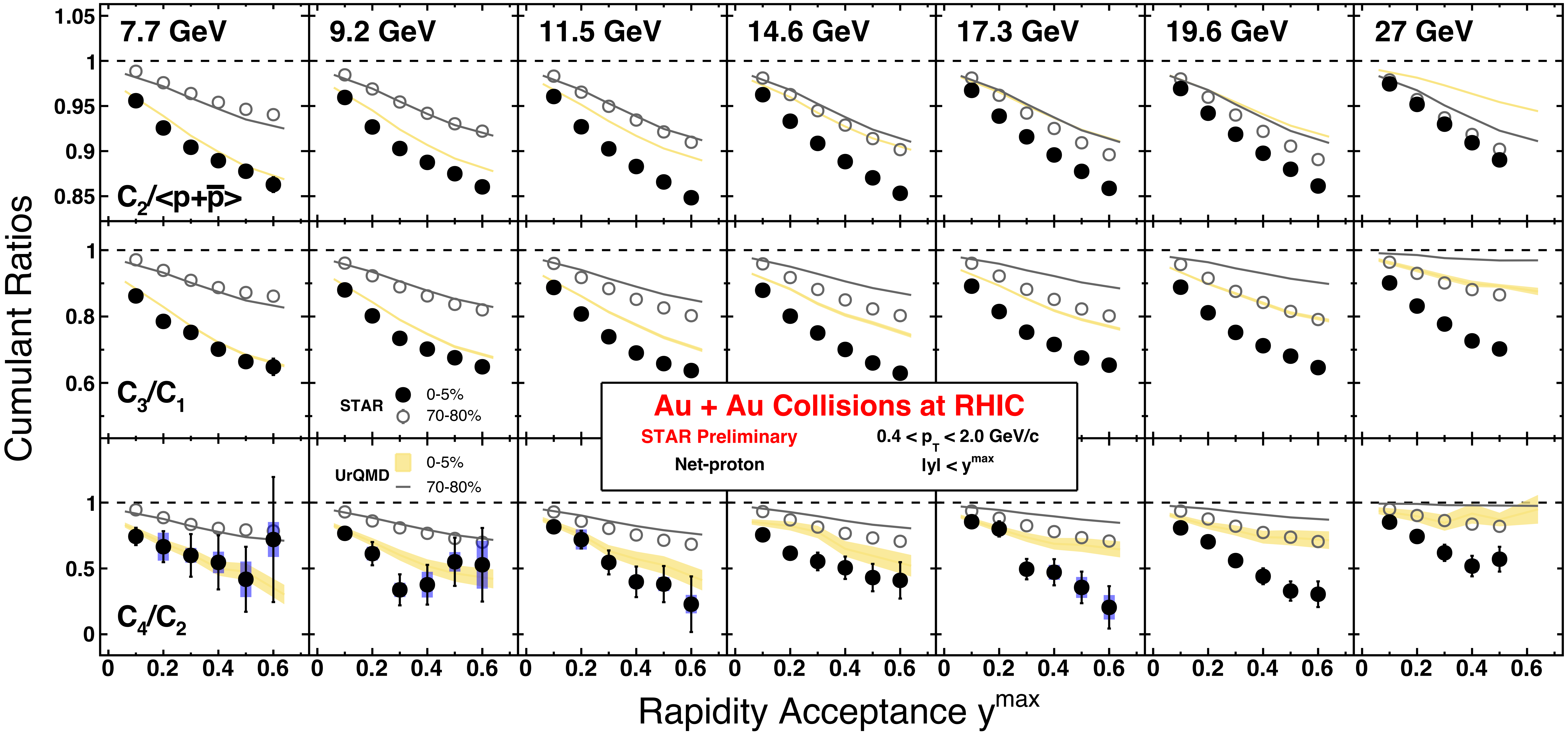




Efficiency Uncorrected Net-proton Number Distributions

1. Left plot: most central collisions across BES-II energies;
2. Right plot: most central collisions at $\sqrt{s_{NN}} = 19.6$ GeV, within various rapidity and transverse momentum ranges.

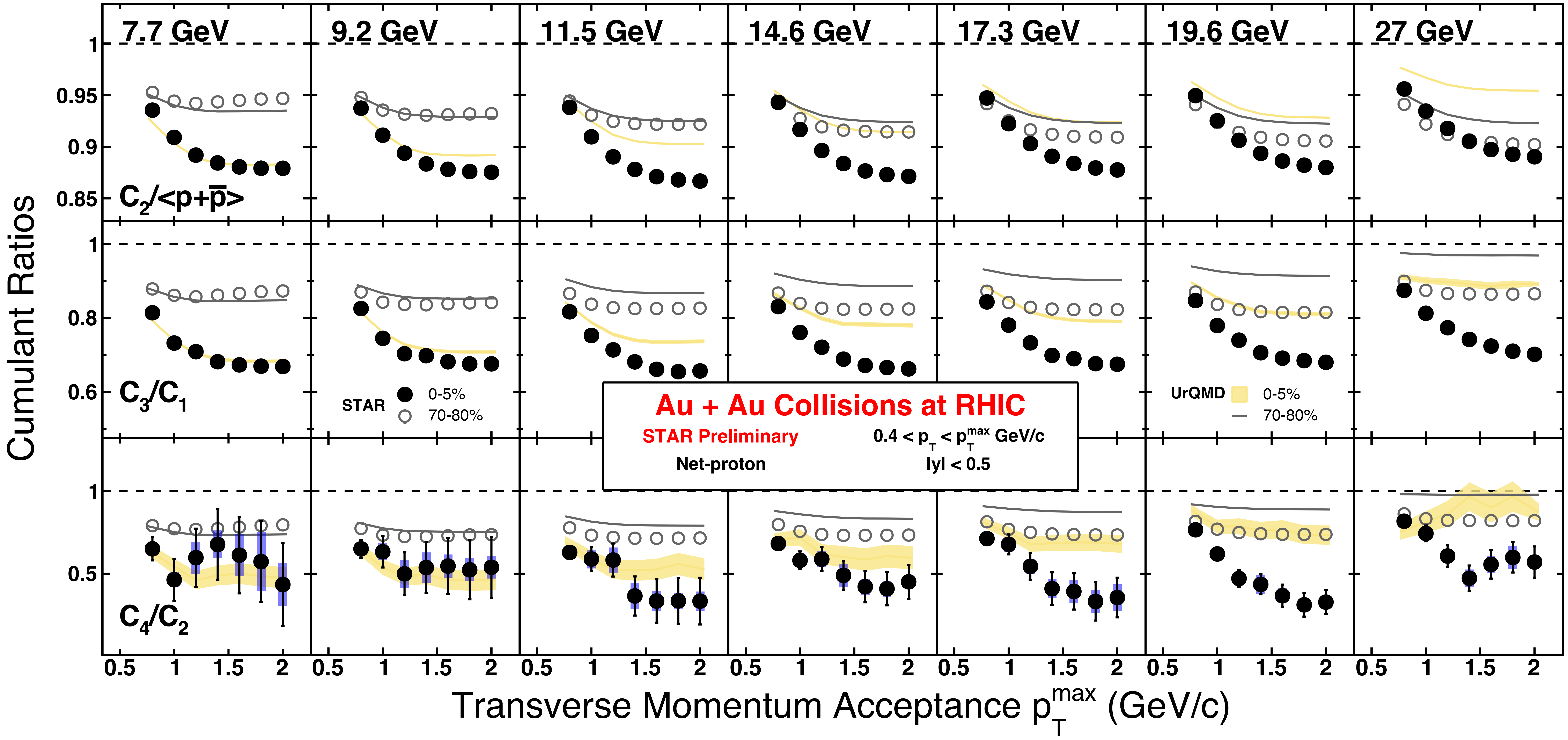
Net-proton Cumulant Ratios: Rapidity Scan



1. Cumulant ratios decrease smoothly along rapidity window;
2. UrQMD[1] describes the trend but fails to quantitatively reproduce the measurement, especially at high collision energy and within wide rapidity range.

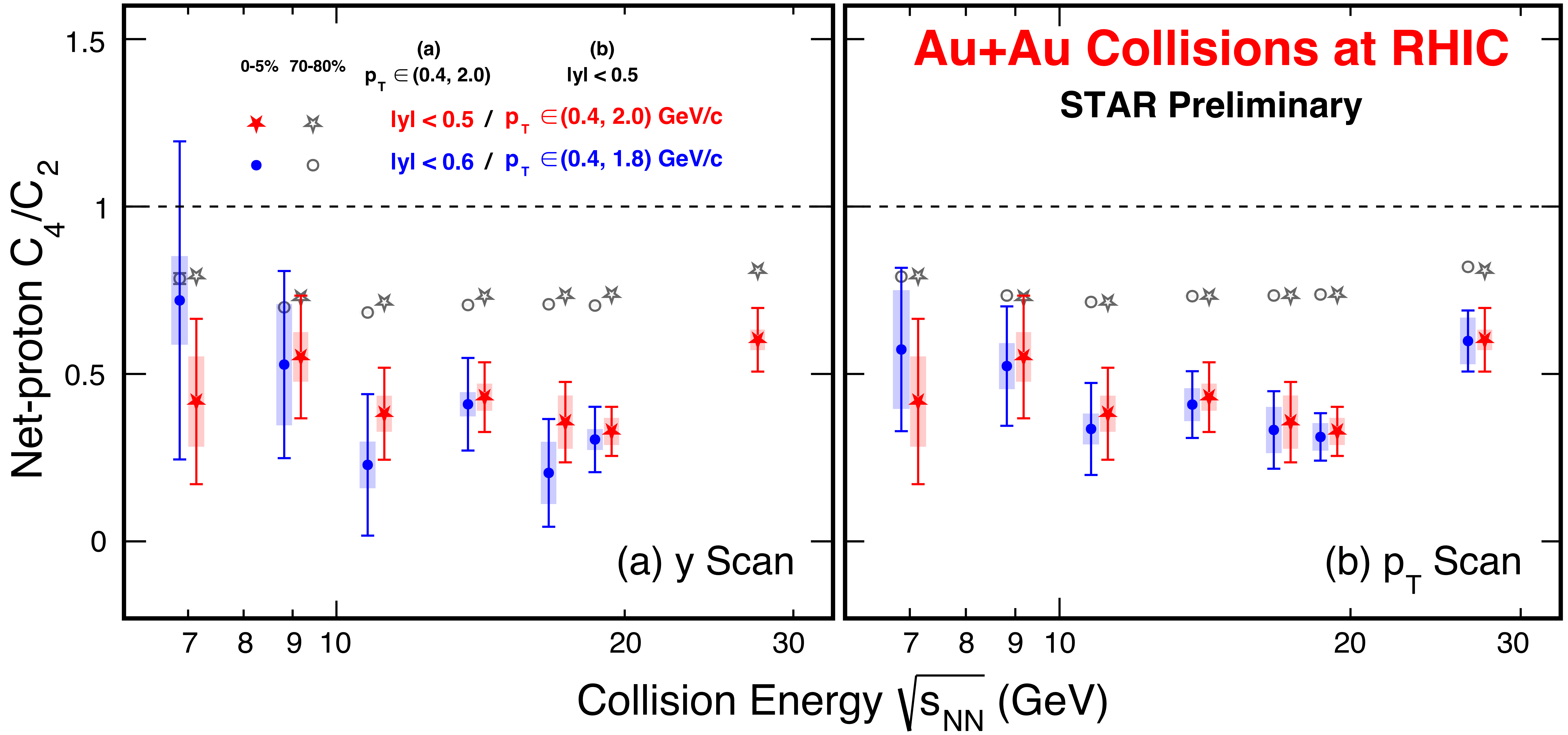
[1]S.A.Bass, et al.: Prog.Part.Nucl.Phys. 41(1998),255-369

Net-proton Cumulant Ratios: p_T Scan



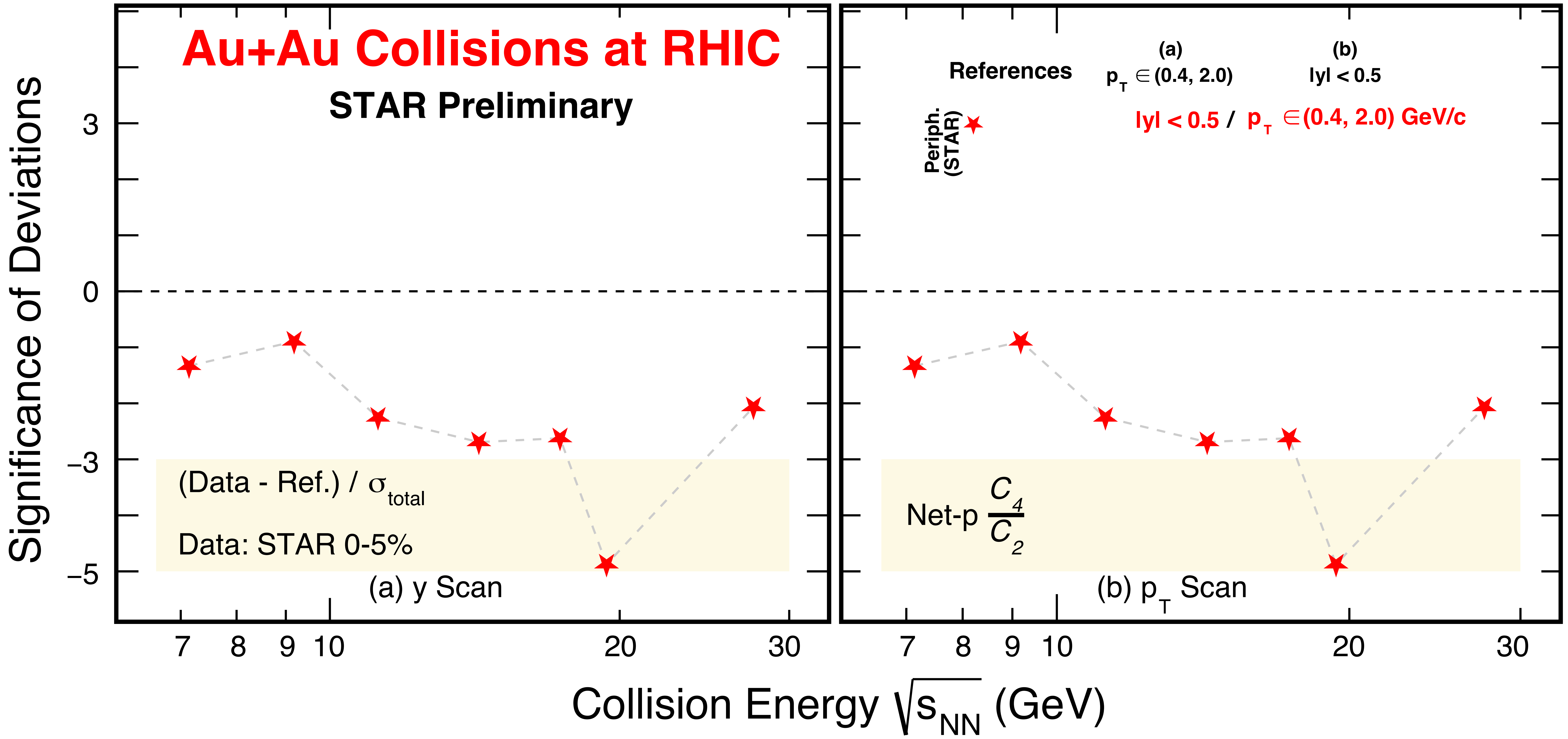
1. Cumulant ratios decrease smoothly along p_T window, and saturate at around 1.8 GeV/c;
2. UrQMD deviates from data in high energy and wide p_T region.

Energy Dependence: Net-proton C_4/C_2



- The wider the y (or p_T) window size, the farther net-proton C_4/C_2 deviates from Skellam baseline.

Energy Dependence: Significance of Deviations



- The largest negative deviation occurs at $\sqrt{s_{NN}} = 19.6$ GeV.

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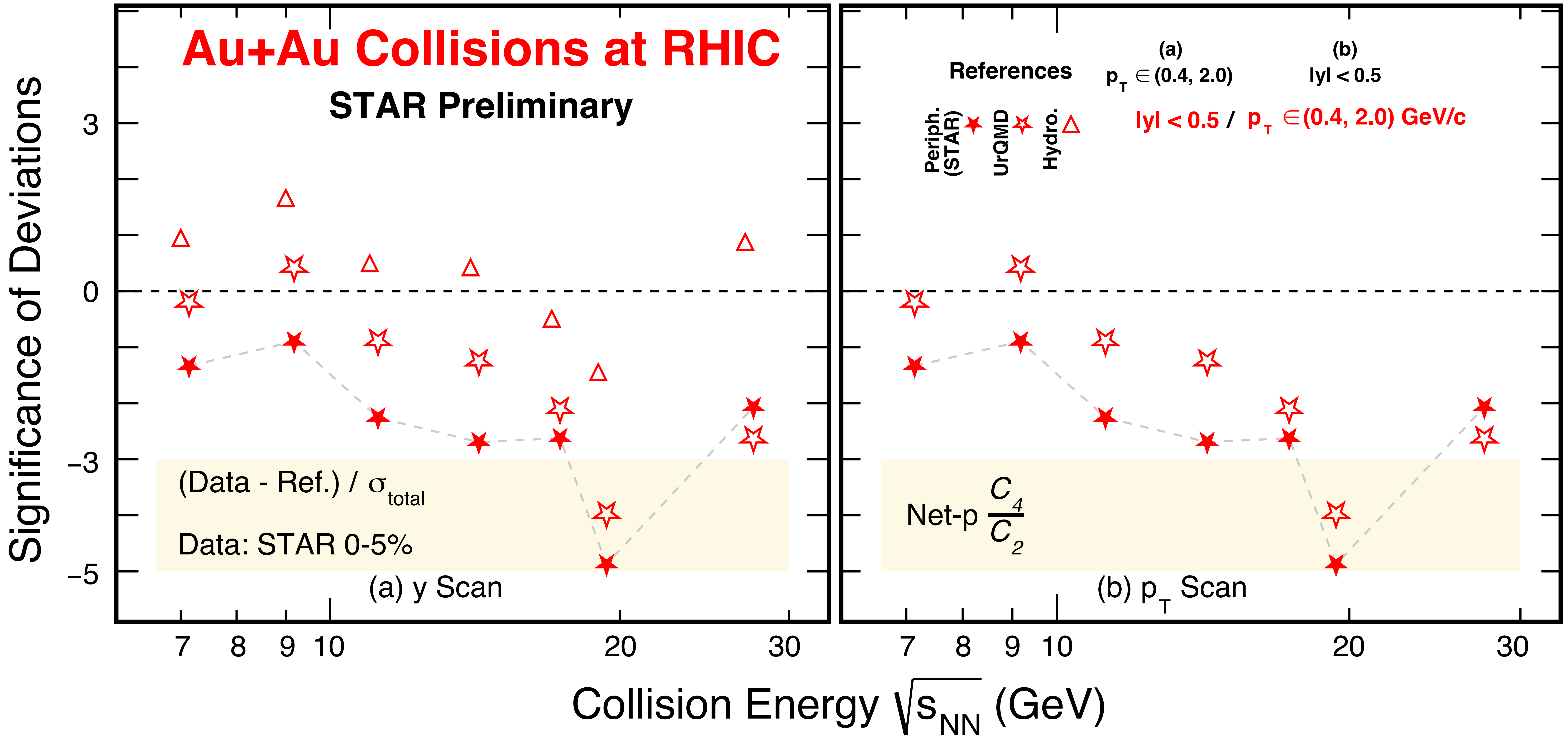

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[3]Hydro. EV: Phys.Rev.C 105(2022)1,014904

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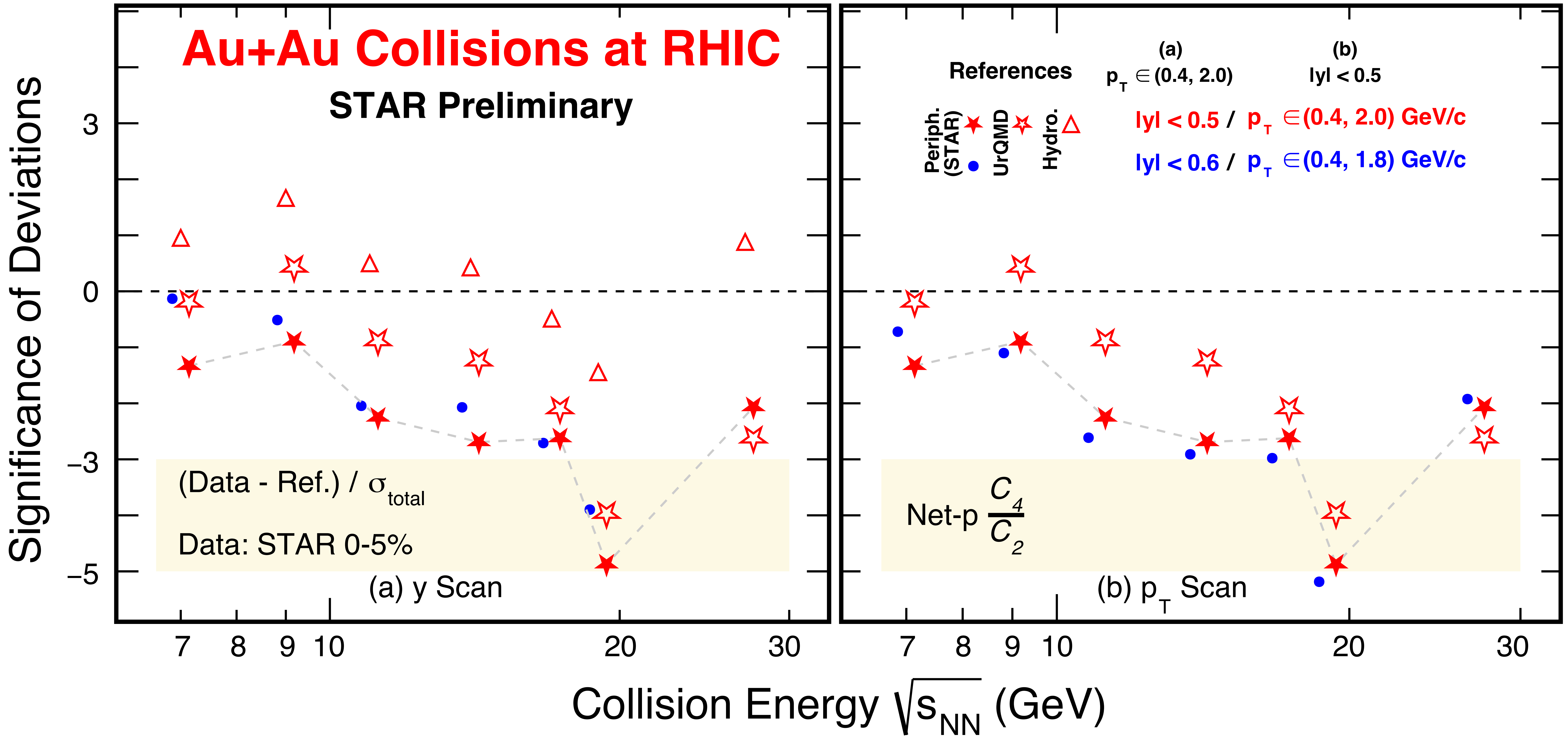

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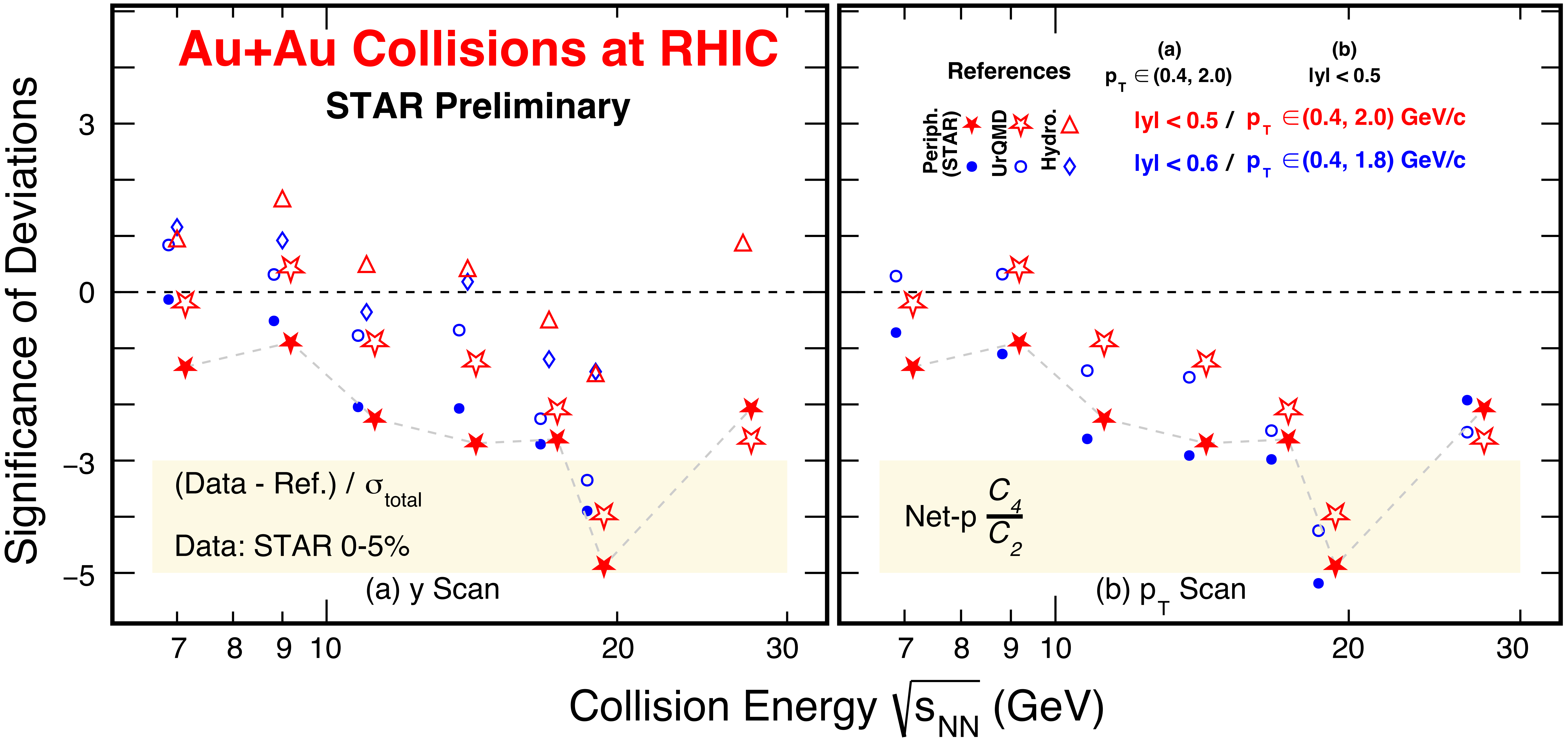

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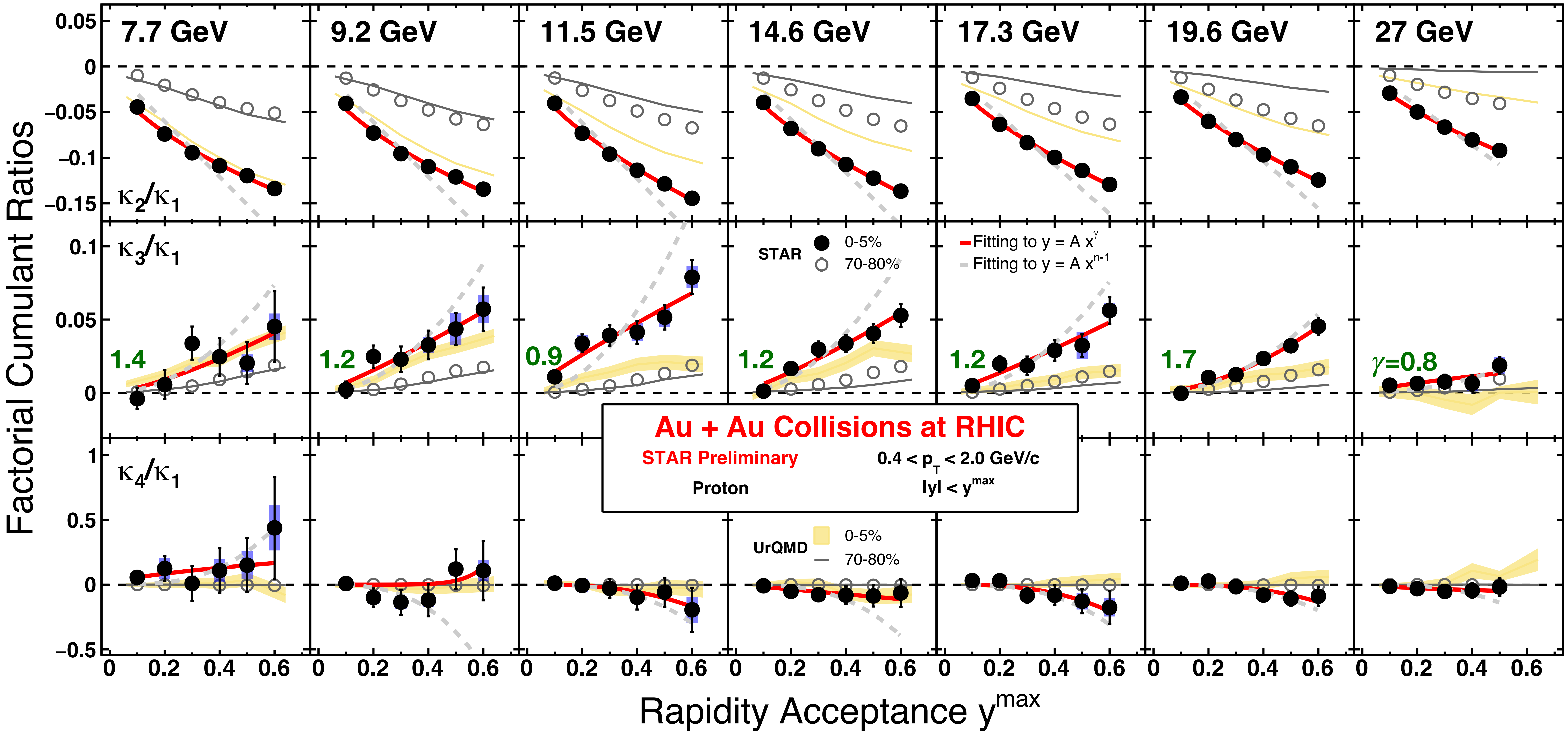
Proton Factorial Cumulant Ratios: Rapidity Scan



Near the critical region, factorial cumulants' dependence on $\Delta y\ (= 2 \times y^{\max})$ is simpler and are suggested to study[1]

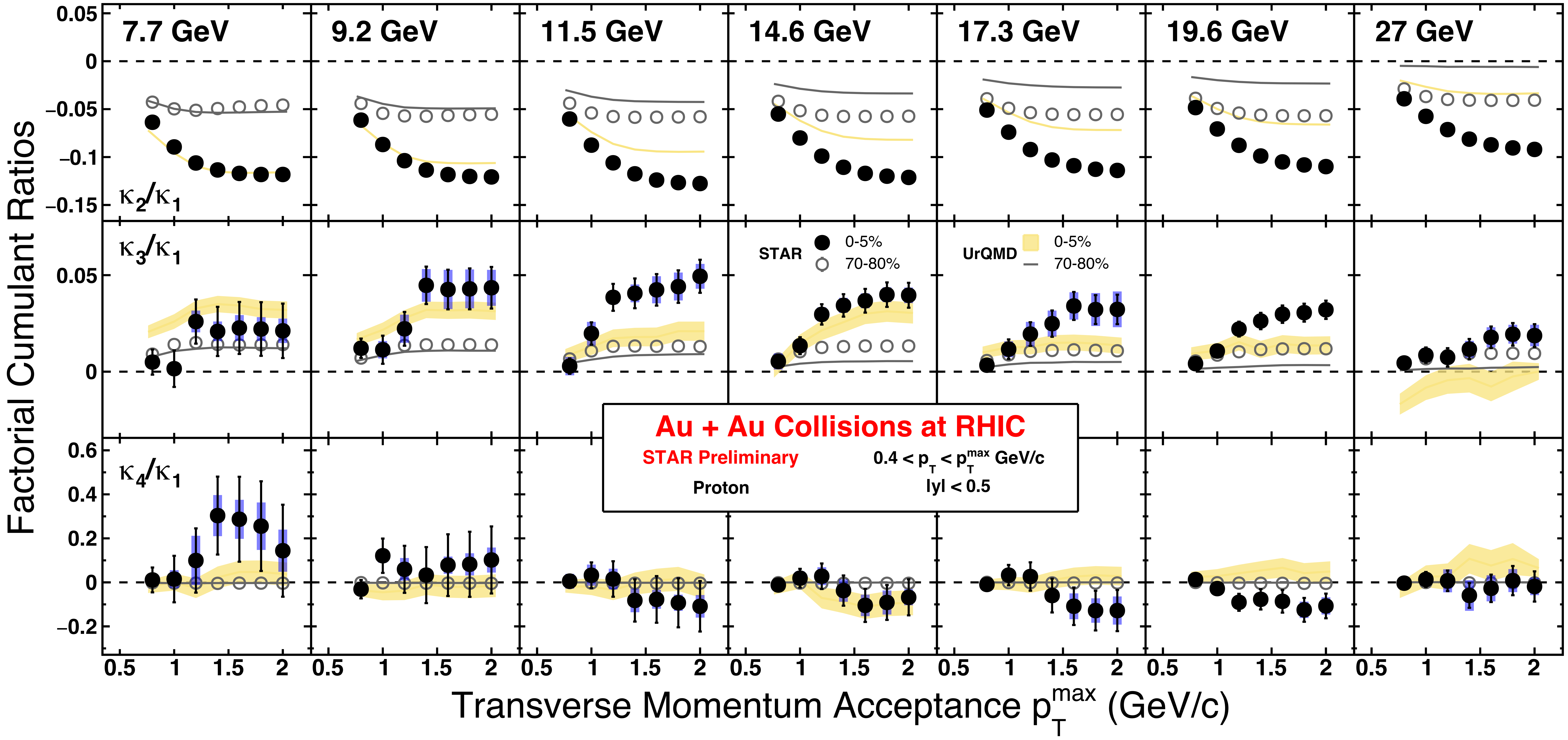
Deep red solid curve (—): Fitting to $y = Ax^{\gamma}$

Light gray dashed curve (- -): Fitting to $y = Ax^{n-1}$

- Smaller exponents than expected power-law $\kappa_n/\kappa_1 \sim (\Delta y)^{n-1}$ are observed.

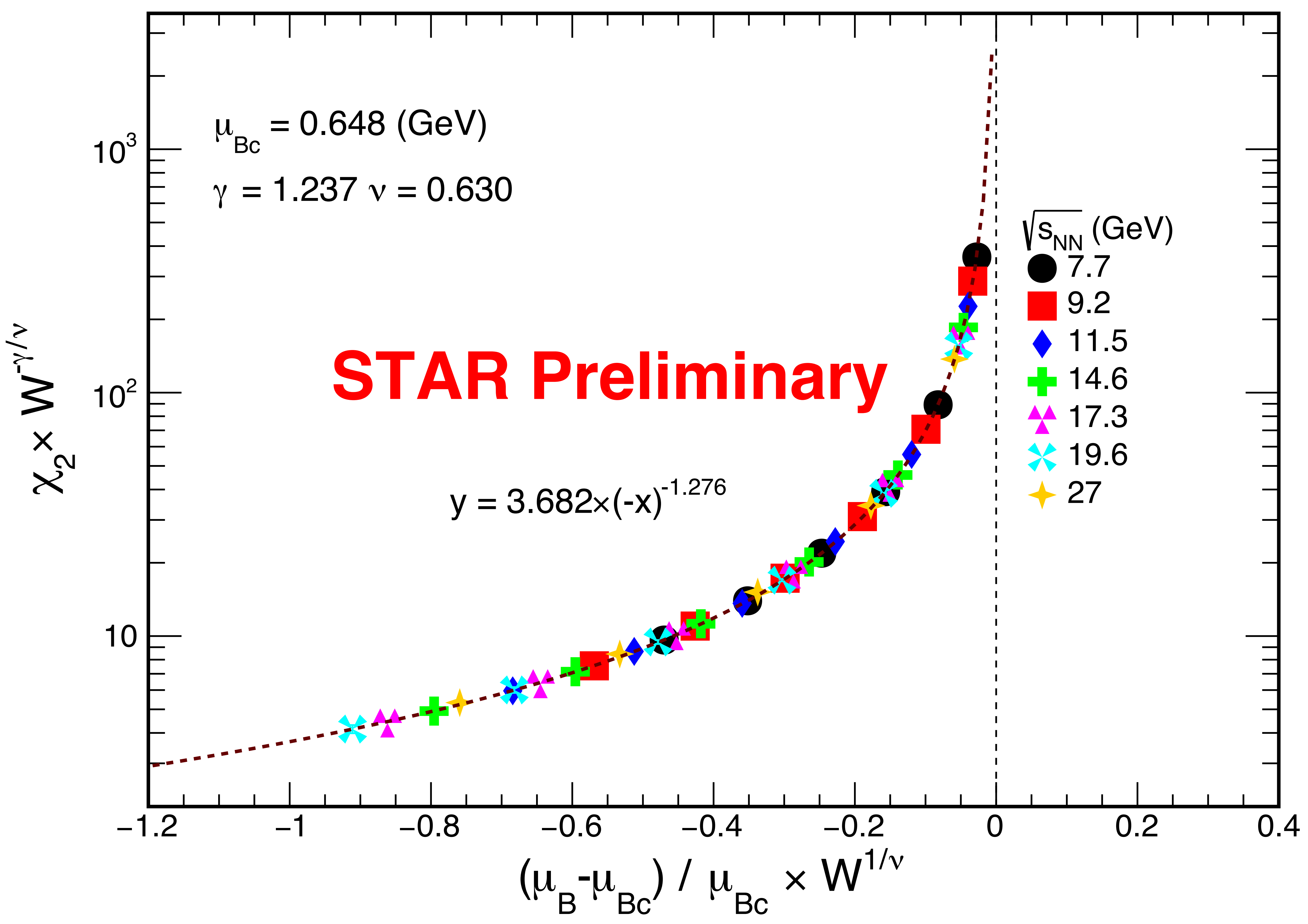
[1]B.Ling and M.A.Stephanov: Phys.Rev.C 93(2016)3,034915

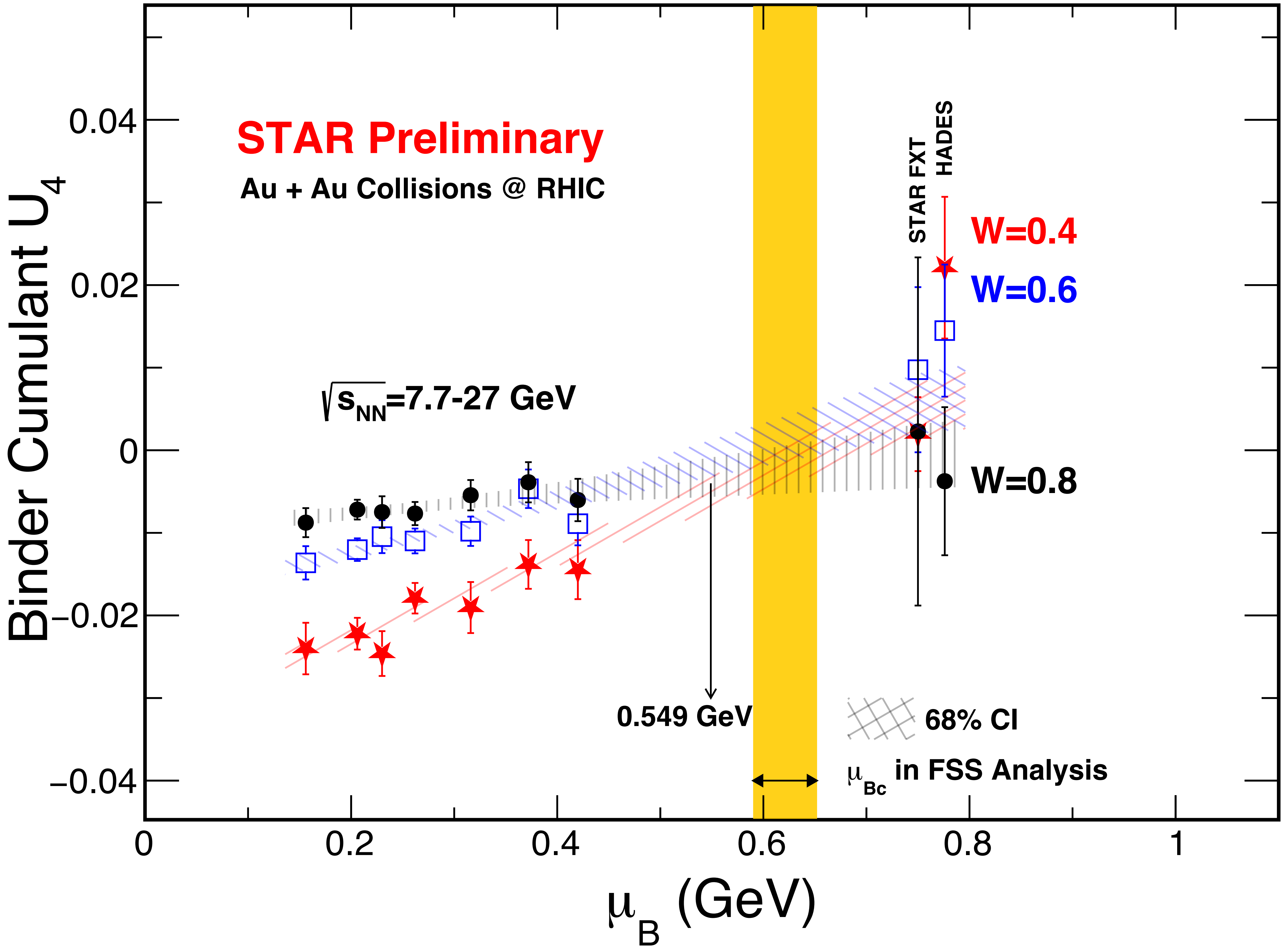
Proton Factorial Cumulant Ratios: p_{T} Scan



1. κ_2/κ_1 is negative, κ_3/κ_1 is positive, and their amplitude increases with increasing window size;
2. κ_4/κ_1 is close to zero and doesn't show significant Δp_{T} dependence;
3. UrQMD can't quantitatively describe STAR data.

Finite-Size Scaling Study





∗:Fit / Systematic uncertainty

1. From FSS study, a $\mu_{Bc} = 648^{+4/+2}_{-3/-58}$ MeV is extracted;
   - $\mu_{Bc} = 625 \pm 60$ MeV in Ref[1] (w/ BES-I data)
2. Consistency observed from the overlap region of $U_4(\mu_B)$.

1) Susceptibility: $\chi_2(W, \mu_{fo}) = \dfrac{C_2(W, \mu_{fo})}{T^3_{fo} W dV_{fo}/dy}$
2) Binder cumulant: $U_4 = -3C_4/C_2^2$
3) Rapidity window size: W
4) Freeze out parameters[1][2]: $T, \mu, dV/dy$
5) Critical exponents[3]: γ, ν
6) Uncertainty: $\sigma = \sqrt{\sigma^2_{\text{stat.}} + \sigma^2_{\text{sys.}}}$

[1]A.Sorensen and P.Sorensen: arXiv:2405.10278[nucl-th]
[2]A.Andronic, et al.: Nature 561(2018)7723,321-330
[3]J.V.Sengers and J.G.Shanks: Journal of Statistical Physics 137,857(2009)
[4]STAR: Phys.Rev.C 107(2023)2,024908
[5]HADES: Phys.Rev.C 102(2020)2,024914

Summary

STAR

1. We report the measurements of kinematic range scan of (net-)proton (factorial) cumulants and their ratios from STAR BES-II;

2. The significance of net-proton C_4/C_2 shows the largest negative deviation at $\sqrt{s_{NN}} = 19.6$ GeV, which is consistent with reported results;

3. Smaller exponents are extracted compared to the critical inspired $\kappa_n/\kappa_1 \sim (\Delta y)^{n-1}$ (up to 3rd order);

4. FSS and Binder cumulant study leads to an interesting region of $\mu_B \sim$ 550 to 650 MeV, which is consistent with Sorensens' work.

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Thank You!